Astronomy & Astrophysics manuscript no. iso˙rev February 5, 2008
(DOI: will be inserted by hand later)

Theoretical isochrones for the Δa photometric system

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Received 2003; accepted 2003

Abstract. We have calculated theoretical isochrones for the photometric Δa system to derive astrophysical parameters such as the age, reddening and distance modulus for open clusters. The Δa system samples the flux depression at 520 nm which is highly efficient to detect chemically peculiar (CP) objects of the upper main sequence. The evolutionary status of CP stars is still a matter of debate and very important to test, for example, the dynamo and diffusion theories. In fact, the dynamo or fossil origin of the magnetic fields present in this kind of stars it still not clear. Using the stellar evolutionary models by Claret (1995), a grid of isochrones with different initial chemical compositions for the Δa system was generated. The published data of 23 open clusters were used to fit these isochrones with astrophysical parameters (age, reddening and distance modulus) from the literature. As an additional test, isochrones with the same parameters for Johnson UBV data of these open clusters were also considered. The fits show a good agreement between the observations and the theoretical grid. We find that the accuracy of fitting isochrones to Δa data without the knowledge of the cluster parameters is between 5 and 15 %.

Key words. Open clusters and associations: general – stars: fundamental parameters

1. Introduction

The chemically peculiar (CP) stars of the upper main sequence have been targets for astrophysical studies since their discovery by the American astronomer Antonia Maury (1897). Most of this interval was devoted to the detection of peculiar features in their spectra and photometric behaviour. The main characteristics of the classical CP stars are: peculiar and often variable line strengths, quadrature of line variability with radial velocity changes, photometric variability with the same periodicity and coincidence of extrema. Overabundances of several orders of magnitude compared to the Sun were derived for heavy elements such as Silicon, Chromium, Strontium and Europium.

The discovery by Babcock (1947) of a global dipolar magnetic field in the star 78 Virginis was followed by a catalog of similar stars (Babcock 1958) in which also the variability of the field strength in many CP stars, including even a reversal of magnetic polarity was discovered leading the Oblique Rotator concept of slowly rotating stars with non-coincidence of the magnetic and rotational axes (Babcock 1949). Due to the chemical abundance concentrations at the magnetic poles spectral and the related photometric variabilities are also easily understood, as well as radial velocity variations of appearing and receding patches on the stellar surface.

The prerequisite for investigating larger samples of CP stars (including the generally fainter open cluster members) is unambiguous detection. Looking into catalogues of CP stars, especially of the magnetic ones, it immediately becomes obvious that there are many discrepancies at classification dispersions. Even the short list of peculiar stars identified by Maury (1897) contains one object which is classified as erroneous in the catalogue of Renson (1991).

The reasons for discrepant peculiarity assessments are to be found in the differences of personal pattern recognition among different classifiers, differences of (mainly photographic) observing material (density of spectrograms, widening of spectra, dispersion, focussing), seeing conditions (for objective prism spectra), and intrinsic variability of peculiar spectral features (e.g. silicon lines).

Photometry has shown a way out of this dilemma, especially through the discovery of characteristic broad band absorption features; the most suitable being located around 520 nm. Two decades ago, Maitzen (1976) introduced a three filter photometric system which samples the depth of this flux depression by comparing the flux at the center (522 nm g_2), with the adjacent regions (500 nm, g_1 and 550 nm, y) using a band-width of 13 nm.

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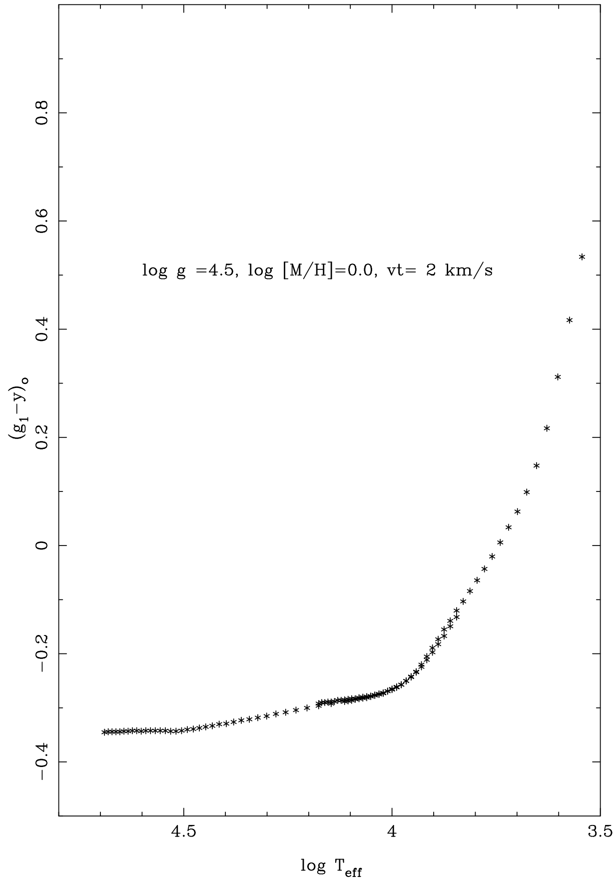

Fig. 1. Theoretical relationship between $(g_1 - y)_0$ and the effective temperature for models with solar abundance, vt $= 2\,\mathrm{kms}^{-1}$, $l/\mathrm{H}_p = 1.25$ and $\log g = 4.5$ dex. For models with $\mathrm{T}_{eff} \leq 8500$ K, an alternative theory of convection was adopted (see text).

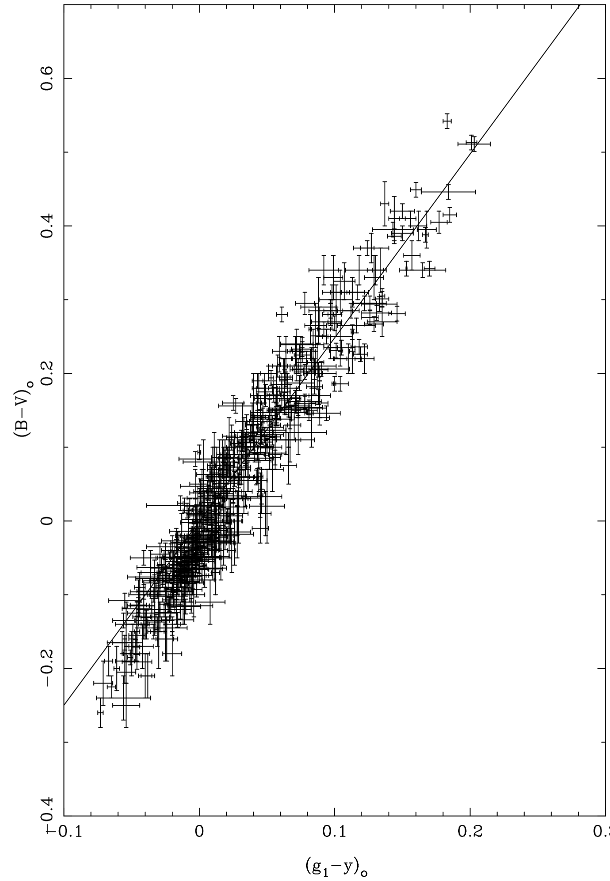

Fig. 2. The empirical $(g_1 - y)_o$ and $(B - V)_o$ data and the respective theoretical predictions (continuous line). The theoretical value was obtained by averaging the whole grid of stellar atmosphere models.

In this paper we have used the published CCD photometry of 23 open clusters (Bayer et al. 2000, Maitzen et al. 2001, Paunzen & Maitzen 2001, 2002 and Paunzen et al. 2002, 2003) together with theoretical isochrones for the Δa system to test the capability of this system to derive the reddening, age and distance for these open clusters. The isochrones are based on the evolutionary stellar models by Claret (1995). We find a very good agreement of the fitted parameters for the Δa system compared to those from the literature for e.g. the Johnson UBV system.

2. Motivation and aim

The Δa system is based on the three narrow band filters g_1, g_2 and y. The respective index measuring the 520 nm depression was introduced as:

$$a = g_2 - (g_1 + y)/2$$

Since this quantity is slightly dependent on temperature (increasing towards lower temperatures), the intrinsic peculiarity index had to be defined as

$$\Delta a = a - a_0[(b - y); (B - V); (g_1 - y)]$$

i.e. as the difference between the individual a-value and the a-value of non-peculiar stars of the same colour (the locus of the a_0-values has been called the normality line). It has been shown that virtually all peculiar stars with magnetic fields (CP2 stars) have positive Δa-values up to 0.075 mag whereas Be/Ae and λ Bootis stars exhibit significant negative ones. Extreme cases of the CP1 and CP3 group may exhibit marginally peculiar positive Δa values (Vogt et al. 1998).

The index $(g_1 - y)$ shows an excellent correlation with $(B - V)$ as well as $(b - y)$ and can be used as an indicator for the effective temperature. The main result of detecting peculiar stars is supplemented by a very accurate color-magnitude diagram (y or V versus $(g_1 - y)$) which can be used to determine the reddening, distance and age of an open cluster.

The evolutionary status of the CP stars has been especially controversial. Oetken (1984) concluded that the CP2 (magnetic CP stars) phenomenon appears at the late stages of the main sequence evolution. Later, Hubrig et al. (2000) found that the distribution of CP2 stars of masses below $3\,M_\odot$ in the Hertzsprung-Russell-diagram differs from that of the presumably normal-type stars in

Table 1. 23 published open clusters with Δa CCD photometry taken from Bayer et al. (2000), Maitzen et al. (2001), Paunzen & Maitzen (2001, 2002) and Paunzen et al. (2002, 2003). The values for the reddening, age and distance modulus are from the same sources. The metallicity for all clusters is (within the errors) solar according to WEBDA and Lyngå (1987).

Cluster	$\log t$	$m_V - M_V$	E$(B-V)$	N_{Stars}	Cluster	$\log t$	$m_V - M_V$	E$(B-V)$	N_{Stars}
Collinder 272	7.20	13.06	0.47	111	NGC 6134	8.97	11.07	0.40	102
Lyngå 14	6.71	14.29	1.48 (var)	53	NGC 6192	7.95	13.00	0.68	98
Melotte 105	8.30	12.70	0.36	114	NGC 6204	7.60	11.50	0.43	319
NGC 2099	8.50	11.67	0.30	41	NGC 6208	9.00	10.54	0.18	41
NGC 2169	7.70	10.57	0.12	13	NGC 6250	6.50	11.18	0.38	48
NGC 2439	7.20	14.23	0.41	113	NGC 6396	7.20	13.34	0.96 (var)	105
NGC 2489	8.45	12.00	0.40	59	NGC 6451	8.13	13.74	0.67	146
NGC 2567	8.43	11.40	0.13	50	NGC 6611	6.90	13.72	0.86 (var)	79
NGC 2658	9.10	11.67	0.04	55	NGC 6705	8.30	12.73	0.43	312
NGC 3114	8.10	10.02	0.07	271	NGC 6756	8.10	14.67	0.80	65
NGC 3960	8.80	12.74	0.30	93	Pismis 20	6.60	15.30	1.24 (var)	238
NGC 5281	7.10	11.35	0.26	30					

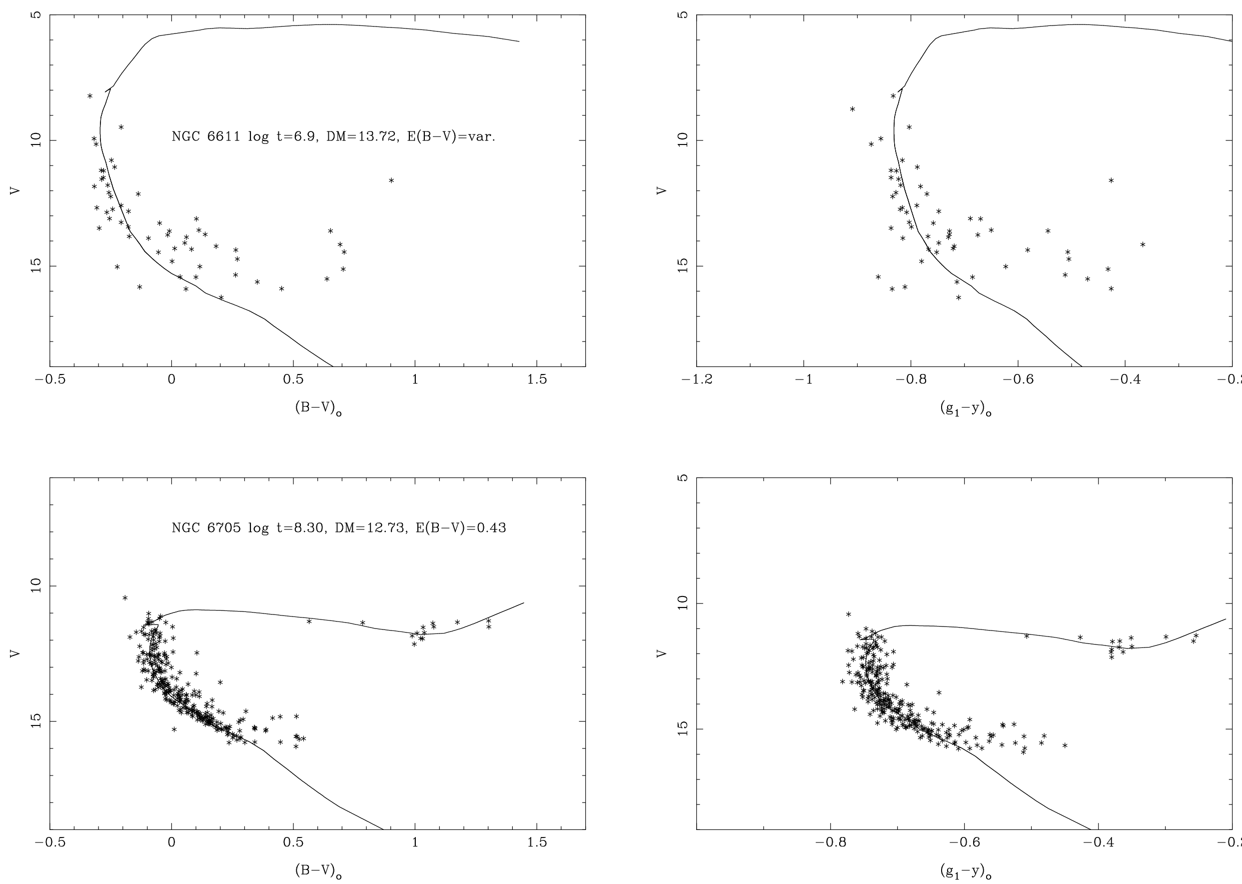

Fig. 4. Isochrones for NGC 6611 and NGC 6705 with the parameters listed in Table 1.

the same temperature range at a high level of significance. Magnetic stars are concentrated toward the center of the main sequence band. In particular, Hubrig et al. (2000) found that measurable magnetic fields appear only in stars which have already completed at least approximately 30% of their main sequence life-time. No clear picture emerges as to the possible evolution of the magnetic field across the main sequence. Weak hints of some (loose) relations between magnetic field strength and other stellar parameters are found: stars with shorter rotational periods tend to have stronger fields, as do higher temperature and higher mass stars. No correlation between the rotation period and the fraction of the main sequence life time completed was observed, indicating that the slow rotation in these stars

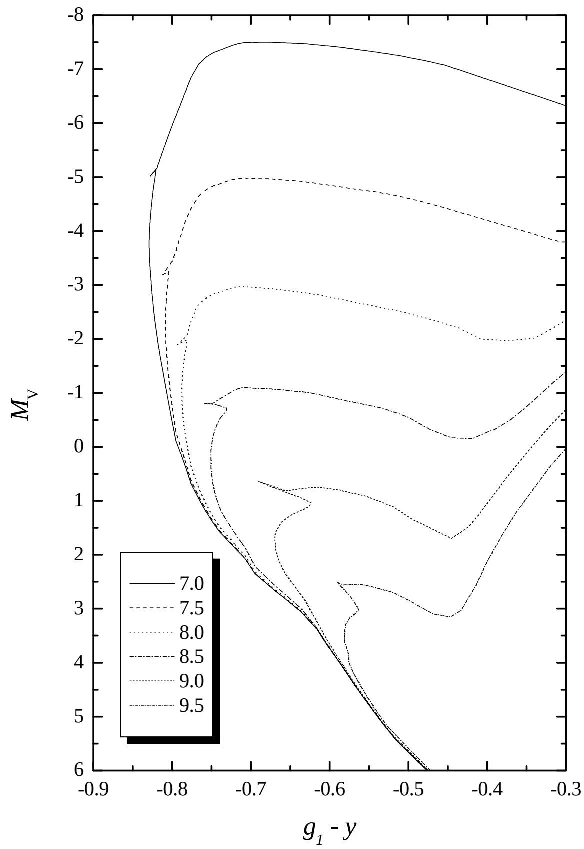

Fig. 3. Theoretical isochrones for different ages and solar abundance for the evolutionary models described in Sect. 3

must already have been achieved before they became observably magnetic. A marginal trend of the magnetic flux to be lower in more slowly rotating stars may possibly be seen as suggesting a dynamo origin for the magnetic field.

The results of the Hipparcos mission on the other hand do not support the mentioned above findings. Gómez et al. (1998) presented the Hertzsprung-Russell-diagram of about 1000 CP stars in the solar neighbourhood using astrometric data from the Hipparcos satellite as well as photometric and radial velocity data. Most CP stars lie on the main sequence occupying the whole width of it (about 2 mag), just like normal stars in the same range of spectral types. Pöhnl et al. (2003) present further evidence that the CP2 stars already occur at very early stages of stellar evolution, significantly before they reach 30 % of their life-time on the main sequence. Pöhnl et al. (2003) investigated four young open clusters with known ages and accurate distances (error < 10%), including CP2 members using the measurements and calibrations of the Geneva 7-color photometric systems to derive effective temperatures and luminosities. Taking into account the overall metallicity of the individual clusters, isochrones and evolutionary tracks were used to estimate ages and masses for the individual objects. The derived ages (between 10 and 140 Myr) were well in line with those of the corresponding clusters.

The finding of CP stars in open clusters is essential to put further constraints on models dealing with dynamo theories, angular momentum loss during the pre- as well as main sequence and evolutionary calculations for such objects.

The age, reddening and distance of open clusters is often controversial (see Paunzen & Maitzen 2002 for the case of NGC 6451) or not even defined at all. We have therefore calculated isochrones for the Δa system to perform such an analysis.

3. Models, data selection and isochrone fitting

The stellar models used to calculate the isochrones have been described in more detail by Claret (1995). We will give here a short overview of the input physics. The chemical composition is (X, Z) = (0.70, 0.02) though different combinations of X and Z can also be used following the metallicity indicator of each cluster. The equation of state takes into account partial ionization through Saha's approximation, the pressure of gas and radiation as well as the equations for degenerate electrons. For less massive stars, a special treatment of the equation of state was adopted through the CEFF package (Däppen 1994 – 2000). Radiative opacities were computed with the OPAL code. The mixing length theory was used to describe convection and moderate overshooting with $\alpha_{ov} = 0.2$ was considered for convective cores. The models take into account mass loss during the main sequence as well as during the red giant phase.

The filter transmission functions of g_1 and y are the same as those used by Kupka et al. (2003). We have performed synthetic colour calculations, using the properties of the mentioned filters, in order to establish the connection between observed and theoretical quantities. A similar procedure as described by Castelli (1999) and Kupka et al. (2003) was adopted. The original ATLAS9 models (see Kurucz 1993), with a microturbulence velocity of 2 kms^{-1}, $-5.0 \leq \log$ [M/H] $\leq +1$ and mixing-length parameter $\alpha = 1.25$ were the basic tools to derive the synthetic colours. For $T_{eff} \leq 8500$ K, we adopted the calculations by Kupka et al. (2003) due to problems detected in the convection model, precisely in the specific intensities (e.g. Claret et al. 1995). These models were computed adopting the Canuto & Mazzitelli (1991) prescription. The implementation of this alternative theory of transport of energy by convection does not significantly affect the hotter models, as expected. In fact, the differences in the respective colour indices are of the order of 1 to 3 mmag, as described and calculated by Kupka et al. (2003). As an example of synthetic colour calculation Fig. 1 shows the dependence of $(g_1 - y)_o$ with the effective temperature for models with $\log g = 4.5$ dex. Similar results are obtained for different values of $\log g$, microturbulent velocities and/or metallicity. Figure 2 shows a comparison between empirical data and theoretical colour indices. The continuous line indi-

cates the average of all theoretical models (in $\log g$). The zero-point was corrected by adding 0.31 to the theoretical $(g_1 - y)$ values. The final isochrones, considering the adequate values of $\log g$ for each class of luminosity, are shown in Fig. 3 for different ages from $\log t = 7.0$ to 9.5, respectively.

Kupka et al. (2003) have shown that metallicities different from solar values shift the normality line by about 3 to 6 mmag for [Z] = ± 0.5 dex. Such an effect is, in general, a factor of two smaller than the intrinsic measurement errors and not detectable. Nevertheless, we have searched through the open cluster database WEBDA (http://obswww.unige.ch/webda/) and Lyngå (1987) for available metallicities of the open clusters listed in Table 1. For none of the investigated clusters, a value different than solar was found within the given error. We therefore expect that all programme clusters have solar metallicity.

We have taken the published Δa CCD photometry together with the Johnson UBV ones of 23 open clusters (Bayer et al. 2000, Maitzen et al. 2001, Paunzen & Maitzen 2001, 2002 and Paunzen et al. 2002, 2003) to test these isochrones. These open clusters have widely different ages and reddening which makes them excellent test cases (Table 1).

The isochrone fitting was performed in two steps. First, we dereddened the $(g_1 - y)$ values according $E(g_1 - y) = 0.4 \cdot E(B - V)$ (Maitzen 1993) and calculated an individual isochrone according to the ages (taken from the literature) listed in Table 1. The data were then plotted with the appropriate distance modulus. In order to test the parameters from the literature, the same procedure was performed for Johnson UBV colors. Figure 4 shows the examples of NGC 6611 and NGC 6705 for both photometric systems, respectively. The isochrones fit, in general, the data very well.

As second step, the Δa data were fitted to the isochrones without an a-priori knowledge of the reddening, age and distance modulus. Here we face the same problems and error sources as for the classical photometric systems since no colour-colour diagram is available. Nevertheless, we were able to reproduce the parameters from the literature with an accuracy between 5 and 15 % depending on the age, available giant members and the presence of differential reddening.

4. Conclusions

We have investigated the capability of theoretical isochrones for the photometric Δa system to derive astrophysical parameters such as the age, reddening and distance modulus for open clusters. The Δa system is highly efficient to detect chemically peculiar objects of the upper main sequence by sampling the flux depression at 520 nm.

Using the stellar evolutionary models by Claret (1995) and the well established filter transmission functions, a grid of isochrones with solar abundances was calculated.

As a test, the published data of 23 open clusters were used to fit these isochrones with parameters from the literature. Furthermore, the appropriate isochrones with the same parameters for the Johnson UBV photometric system were considered. The fits show an excellent agreement between the observations and the theoretical grid.

In addition, we have fitted the observational data without the knowledge of the age, reddening and distance modulus yielding an accuracy of 5 to 15% depending on the well known error sources of such a method.

Acknowledgements. EP acknowledges partial support by the Fonds zur Förderung der wissenschaftlichen Forschung, project P14984. The Spanish DGYCIT (PB98-0499) is gratefully acknowledged for its support during the development of this work. We are grateful to F. Leone and B. Willems, who have helped to improve the final version of the paper. Use was made of the SIMBAD database, operated at CDS, Strasbourg, France and the WEBDA database, operated at the Institute of Astronomy of the University of Lausanne.

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